SECTION 4

BACKGROUND, PREVIOUS STUDIES, AND RESEARCH

This section presents technical background about the bases for the design of biofiltration swales and summarizes previous studies in the area of biofiltration, including design methods and studies related to Manning's n.

BACKGROUND

Swale design is a problem of open channel flow. The basic formula of open channel flow, introduced to the science of fluid mechanics more than 100 years ago, is Manning's Equation. Manning's Equation expresses the relationship among all of the principal design variables named above, except swale length. Its form in English units of measure is:

$$V = (1.49/n) * R^{0.67} * s^{0.5}$$

where V=velocity (feet per second); n=Manning's coefficient, accounting for vegetational friction (dimensionless); R=hydraulic radius, the ratio of cross-sectional area to wetted perimeter (ft), and s=channel slope (ft vertical/ft horizontal, dimensionless). The equation is commonly stated in terms of volumetric flow rate (Q, ft^3/s) by multiplying by cross-sectional area (A, ft^2):

$$Q = (1.49/n) * A * R^{0.67} * s^{0.5}$$

Manning's Equation offers several advantages but has some drawbacks as a basis for biofiltration swale design. One advantage is its simplicity while still incorporating the key performance variables. Another is its long history of use and wide acceptance. There is substantial empirical evidence of its ability to represent open channel flows well and data to choose Manning's coefficient. However, the available data fall short of covering the many vegetation species or mixes of species that could be planted in biofiltration swales, or of representing the different densities at which vegetation communities could develop. Also, almost all of these data have been collected for flows that exceed the vegetation height, in contrast to the situation in biofiltration swales, where it is essential that flow be shallower than standing vegetation in order to maximize filtering action and promote other pollutant removal mechanisms. Manning's Equation was developed for and has usually been used to design channels for the purpose of transporting water rather than holding it for an adequate length of time for pollutant removal. Thus, few data exist for the case where frictional shear resistance is higher because flow passes through rather than over vegetation.

As pointed out by Minton (personal communication), Manning's Equation has another drawback for biofiltration design purposes, which can be seen by a rearrangement:

$$R = \left[(V * n)/(1.49 * s^{0.5})\right]^{1.5}$$

With other variables held constant, the swale size, represented by R, will decrease if the s value increases. Then A would also decrease, and, with constant Q, V (= Q/A) would increase and reduce residence time, to the detriment of treatment effectiveness. This drawback can be overcome by placing restrictions on V, as recommended by Horner (1988), or establishing a residence time criterion, or both.

Recognizing these disadvantages, but taking note of how they can be overcome, the Project team concluded that Manning's Equation was the best available basis for designing biofiltration swales. Only one alternative, the University of Kentucky method, exists at present. It is discusses below after results of the Phase I Biofiltration are summarized.

PHASE I BIOFILTRATION STUDY (Horner, 1988)

In 1988, Metro, along with King County and the Cities of Redmond, Mountlake Terrace, and Bellevue, contracted with Dr. Richard Horner to provide a review of the application of biofiltration for stormwater management, including the presentation of preliminary design criteria. That study, funded in part by a Centennial Cleanwater Grant, provided a review of the literature, an inventory of grassy swales that had been constructed in the Seattle metropolitan area up to that time, management guidelines, and a preliminary design methodology. Each of these areas is summarized briefly below.

Literature Review

Insight into the mechanisms and treatment potential of biofiltration systems comes largely from the wastewater treatment literature. Land treatment of wastewater has been comparatively well studied (Barfield et al., 1975, Bouwer, 1976, Lee et al., 1976, Metcalf & Eddy, 1977, USEPA, 1980, Smith & Schroeder, 1985). Filter strips, also a form of biofiltration, have also been investigated for use in agricultural and feed lot management (Dillaha et al., 1988, Goldman et al., 1986, Scott & Fulton, 1971). In these applications, biofilters have been effective in removing solids, metals, nutrients, organics and microorganisms.

The most significant local work establishing the pollutant removal capabilities of grassy channels for stormwater applications was a study by the University of Washington for the Washington State Department of Transportation

(Wang et al., 1981). The study found that grassy channels were superior to mud or concrete-lined channels for removing metals from stormwater runoff. The grassy channel studied was not specifically designed for filtration or water quality improvement; nonetheless, results were promising. Solids and lead were consistently removed, and in 60 meters (200 feet), 80 percent removal was demonstrated. Copper and zinc were reduced by 70 percent and 60 percent, respectively. Other studies of pollutant removal in stormwater applications included Harper et al. (1985) and Post et al. (1982).

Regional Inventory of Swales

Descriptive information of 51 biofilters was presented in the Phase I report. Most (75 percent) were grassy swales, and were specifically designed for pollution control purposes. Overall, few problems were observed in the swales surveyed. Of the problems that were seen, poor vegetation coverage, persistent pooling of water, blockage of curb cut inlets and siltation were the most common.

Management Guidelines

The Phase I report summarized management recommendations in several areas: Institutional and planning, technical considerations, design and installation, and operation and maintenance. General recommendation included the following:

- Maintain flexibility to design the most suitable biofilter configuration for each site
- Make commitments to apply biofiltration locally and provide needed education on the technique
- Emphasize inspection and maintenance, which often advance success more than any other factors
- Use natural swales and roadside ditches for pollution control purposes
- Consider opportunities to fit biofiltration to developed sites retroactively, and to fit low-flow swales within retention/detention ponds

Preliminary Design Criteria

The design process recommended in the Phase I report adapts a procedure first introduced by Chow (1959). It involves the application of Manning's Equation to a 2-year, 24-hour design storm flow in an iterative process constrained by a specified maximum velocity of 1.5 feet per second, and slopes between 2 and

4 percent. A table presenting Manning's n for different grass types and heights, taken from United States Department of Commerce (1961) was given. Water depths were limited to a maximum of 2 inches below the design grass height. A check for channel stability at the maximum design flow was the last step in the design.

OTHER LITERATURE

After the Phase I report was completed, two additional studies investigating the pollutant removal performance of grassy swales were found (Oakland, 1983, Kercher et al., 1983). Table 4-1 summarizes results from these studies in addition to the Wang et al., and Harper et al. studies identified in the Phase I report. Only data for total suspended solids and the metals lead, zinc, copper and iron are presented, these being the most consistently investigated. The Oakland study found poor removal of total suspended solids. Low solids removals were attributed to scouring of channel bottoms in the newly established swales investigated. Good removal of dissolved metals was seen; this was presumably due to amelioration of a low pH runoff (mean 4.0).

Table 4-1. Studies of Biofiltration Effectiveness

Study	Location	Percent Removal					Remarks
		TSS	Lead	Zinc	Copper	Iron	
Wang, et al. (1981)	Seattle	—	80	70	60	70-75	Removal primarily of particulate metals
Oakland (1983)	New Hampshire	33	65	51	48	—	Low solids removals could be attributed to scouring of soil because the grass was newly established. Removal primarily of dissolved metals, but pH quite low (4.0).
Kercher et al. (1983)	Florida	99	99	—	—	99	Removals determined measured outputs and estimated inputs.
Harper et al. (1984)	Florida	—	90	90	30-40	75	Removal of dissolved as well as particulate metals

OTHER DESIGN METHODS

Another approach to vegetated swale design was developed at the University of Kentucky (Barfield et al., 1975, Toller, 1977). This method requires information about grass blade density, in addition to using the resistance force applied by the vegetation blades on the water, the volume of water among the grass blades, the sheer factors due to the channel walls and bed, and other parameters related to channel geometry (Kao & Barfield, 1978).

Subsequent to the Phase I report, the City of Seattle contracted with Resource Planning Associates to assemble a *Water Quality Best Management Practices Manual* (1989) which included the provision of grassy swales. Dr. Minton, the principle author, took issue with a site by site application of the design method suggested by Horner. He argued that since there were uncertainties inherent in applying the design to a treatment situation rather than a water conveyance situation, for which it was historically developed, a general rather than exact application to design situations was more appropriate. Minton provided a rule of thumb approach, also based on the application of Manning's Equation. This rule of thumb method specified swale widths for different combinations of slope, flow resistance, and cross section. The widths were calculated using Manning's n values of 0.30 and 0.40, a 200-foot swale length and a 6-month, 24-hour design storm flow.

The difference in the two methods is not so much in the engineering basis of the design, which is essentially the same, but in the amount of work required for the design. With the Horner method, all swales are designed individually. With the Minton method, swale width is simply taken from a table. Some specificity is lost with the latter method, but given the argued inconsistencies in applying the design method to a water treatment situation, Minton believes the loss is within the precision of the application, and is acceptable.

Using several examples of various size developments for two conditions of slope, the Horner and Minton methods were compared (see Appendix A). It was found that although the Minton method consistently resulted in swales with greater area requirements, the difference was generally less than 10 percent for drainage areas less than 5 acres. However, the size differential grows as the contributing area increases.

Recall that Minton recommends using Manning's n values of 0.3 and 0.4, whereas Horner recommends an n value related to grass density, generally about 0.10. The comparison was repeated using the *King County Surface Water Design Manual*'s recommended Manning's n value of 0.35 instead of 0.10 in the Horner method. This case resulted in significantly greater land requirements than both the Horner and Minton methods, ranging from two to eight times as large, depending on drainage area, slope and flow depth (see Appendix A). Thus the choice of Manning's n seems to have as great an impact on swale size requirements as the design method itself.

STUDIES RELATED TO MANNING'S n VALUE

Numerous researchers have performed field and theoretical studies to determine the value of Manning's n in different types of channel surfaces and materials, including grass-lined swales. A cursory review of the literature shows that for grassy swales, n values range from 0.10 to 0.63 (Table 4-2). The wide range of n values relate in part to the purpose of the application; most studies were for purposes other than water quality treatment.

Ree and Palmer (1949) investigated flow through vegetated waterways in the 1940s for a variety of vegetation, velocities, and flow depths. Their emphasis was on grass lined waterways as conveyance channels rather than biofiltration devices, but some of their test cases are relevant to stormwater treatment applications. For fully submersed grass, a Manning's n of 0.035 was seen, with higher n values for different types and densities of vegetation. A 4-inch grass mix showed a range of Manning's n values between 0.06 and 0.20 at velocities ranging from 6 feet per second to 1 feet per second. A good relationship between Manning's n and the product of flow velocity times hydraulic radius was seen.

Thompson (1974) also investigated the resistance factors in grassy swales using plastic rods. Results are not directly applicable, however, to field situations.

Previous research on a Manning's n value specific to the Puget Sound area has not been identified. Horner (1988) recommends an initial value of 0.10 with greater accuracy for the n value being obtained by using grass height, maximum water velocity, and hydraulic radius of the channel, based on work by Chow (1959) and USSCS (1954). Huckell, Weinmann & Associates (1990) have listed n values recommended by the state, county, and city governments in the Puget Sound area in *Guidebook, Water Quality Swales* (1990). Recommended n values range from 0.07 to 0.35. Table 4-3 summarizes this information.

Table 4-2. Research Groups Investigating Manning's n Value

Research Group and Location	Manning's n Range	Velocity (ft per sec)	Depth Range (ft)	Purpose of Study	Comments	Research Date
Ree and Palmer USSCS-USDA	0.27-0.28	0.23-0.43	0.14-0.36	"Bio-protection" of drainage ditches from channel scour and erosion/ non-sub-merged flow	Data shown 12-inch-long Bermuda grass[1]	1939
	0.04-0.05	1.72-4.46	0.50-1.00	Same as above but with submerged flow	Data shown here with 4-inch long Bermuda grass[2]	1939
Barfield and Kao, University of Kentucky	0.1-0.5			Computer simulation to predict hydraulic resistance of grass caused by blade stiffness and density under submerged and non-submerged flow conditions	n value found to increase with depth under non-submerged conditions and decrease with depth with submerged flow conditions. Resistance found to be independent of slope.[3]	1974-175
Engman[4]	0.39-0.63	Not given	Not given	Hydraulic roughness coefficients from plots used for erosion studies for agriculture and range management	Determined n values from volume of delayed run-off from erosion plots n value given here for bluegrass sod; recommends n=0.45, use where slope is less than 300 feet long[5]	1984-1985
	0.17-0.34			Sheet flow on different grass types	n value shown for Bermuda grass; recommends 0.24	
Current Study	0.2-0.3	0.1-0.5	0.08-0.55	Optimal removal of urban stormwater contaminants	Current value of 0.20 for low maintenance bio-swale	1991-1992

Footnotes:

1. Field research was performed in South Carolina. Channel B2-7 had a slope of 0.03, bottom width of 4 feet, side slopes of 1.5:1. Reference is made to Experiment 2, Tests 1-4, performed March 1939. Grass is dormant and uncut at 12 inches long with an estimated 350 stems/ft^2.
2. Channel B2-7 was used. Experiment 3, Tests 2-5 performed October and November, 1939. Submerged vegetation. It had been mowed once, grass height was 4 inches and estimated blade density of 250/ft^2.
3. Used a model with 1224 grass blades/ft^2 with submerged flow.
4. Data from USDA Agricultural Research Service stations at West Lafayette, IN, Oxford, MS, and Tucson, AZ. Plots were 35-70 feet long, 5-12 feet wide.
5. Rainfall applied to plots with 2 to 4 inches/hour intensity after thorough wetting of soil. Depth, velocity, and slope information not given.

Table 4-3. Manning's n Values Required by Puget Sound Area (Washington) Government Agencies

Agency	n Value Requested	Source
Washington State Department of Ecology	0.07-0.7	Stormwater Design Manual
King County Surface Water Management	0.35	King County Stormwater Design Manual
City of Redmond Public Works, Stormwater Division	0.28-0.35	Unpublished development review guidelines
City of Mountlake Terrace Public Works	0.07	Stormwater Design Manual or development guide
City of Bellevue Stormwater Utility	0.33	Stormwater Design Manual or development guide

SECTION 5

POLLUTANT REMOVAL STUDY

This section presents the pollutant removal data for the grassy swale studied, including a description of the experimental set up and sampling methods, results, discussion and conclusions.

BACKGROUND

This aspect of the study sought to determine the pollutant removal effectiveness of a well designed grassy swale during typical storm conditions. Surprisingly, the selection of the monitoring location was one of the most challenging aspects of this project. Because the Phase I criteria were relatively new, and not all jurisdictions required developments to provide biofiltration swales, geographic selection was limited. After extensive research, observations, and consideration, one swale that met both the design criteria and practical requirements for monitoring was chosen for this study.

The swale is located within the City of Mountlake Terrace, Washington, on 48th Avenue W near 232nd Street SW (Figure 5-1). The drainage area that drains into the head of the swale is 14.7 acres, with an additional 0.8 acres draining directly into the swale along its eastern side. Land use is primarily single family residential with smaller amounts of multi-family residential and park property. A major arterial runs the full length of the drainage basin.

The swale was designed by City of Mountlake Terrace engineering staff according to City design standards (*Water Quality Design Manual,* 1991) using Manning's Equation, with flow estimation by the U. S. Soil Conservation Service (SCS) method for the 2-year, 24-hour design storm.

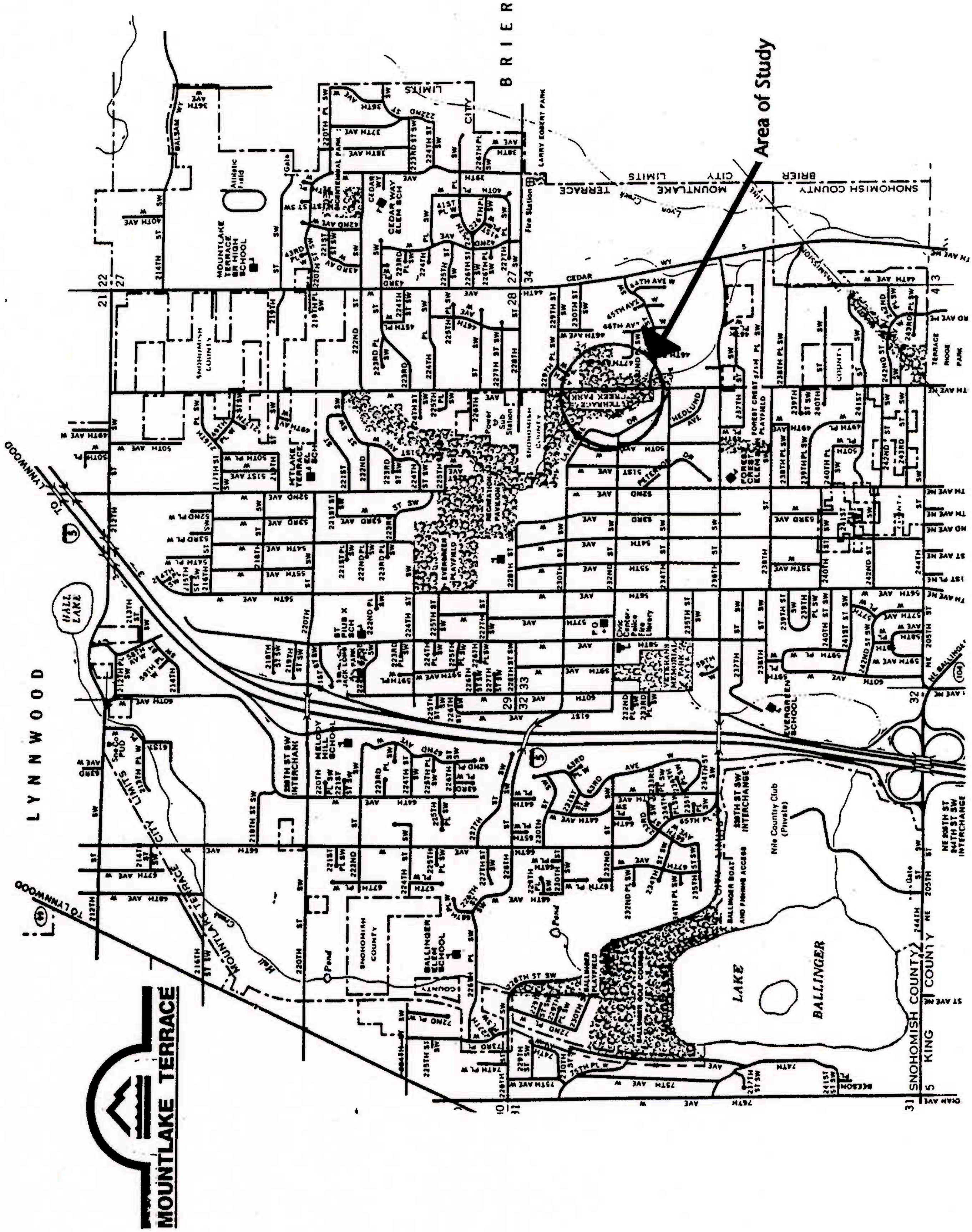

Figure 5-1. Vicinity Map

Detailed design steps are given in Appendix B. Specific design parameters are listed below.

Depth of flow:	0.25 feet
Side slope:	3 horizontal to 1 vertical
Manning's n:	0.07
Maximum velocity:	1.5 feet per second
Freeboard:	1 foot
Shape:	trapezoidal
Bottom width:	5 feet
Longitudinal slope:	3.6 percent upper, 4.3 percent lower swale
Length:	200 feet
Seed mix:	tall fescue,—67 percent seaside bentgrass—16 percent meadow foxtail—9 percent Alsike clover—6 percent marshfield big trefoil—1.5 percent
Watershed area:	14.7 acres at head, 15.5 at outflow
Impervious area:	6.5 acres
Design storm flow:	1.72 cfs

The swale was constructed in the summer of 1989 and seeded the following fall. Water was diverted from the swale through a high flow bypass for the winter months to allow good grass establishment. Sample collection began in the spring of 1990. Grass was mowed twice during the growing season, in June and October.

EXPERIMENTAL SETUP AND SAMPLING METHODS

The study sought to determine if a 200-foot swale length could be replaced by a shorter, 100-foot swale without compromising performance, provided a proportionate increase in width was provided. Since it was not possible to find several swales of varying lengths that were designed using the Phase I design criteria, the single 200-foot swale was instead modified to explore the question of performance at shorter lengths.

Under ideal conditions, the width of the shorter swale would have been doubled to compensate for the decreased length and provide equivalent treatment area. However, the swale width was fixed, and it was not possible to widen the swale for this study. Instead, what was hoped were hydraulically equivalent modifications were pursued.

The relationship $Q=V*A$ (flow equals velocity times area) is a fundamental relationship in hydraulics. Assuming velocity does not change, decreasing the discharge should have an effect equivalent to increasing the effective swale area. So, instead of doubling the swale width, the flow was decreased by one half.

Flow was split by modifications in the catch basin and manhole just upstream of the swale. The drainage system at that point collects all flow from the watershed and delivers it into the manhole through two pipes. Another two outflow pipes take this flow, one to the swale, and one to a slightly higher bypass pipe in the street. Two weirs having equivalent opening size and invert elevations were installed in the outflow pipes. This arrangement effectively split the flow between the swale and the bypass pipe for the entire hydrograph. Details of the flow splitter design are presented in Appendix B.

However, after data were collected and analyses were being carried out, it was realized the hydraulic detention times of the 100-foot swale configuration were about half the residence times for the 200-foot swale configurations for all six storm events, a highly unlikely outcome if the above reasoning were indeed accurate. Upon further examination, it was found that by decreasing the flow Q, water depth was also decreased by the same proportion. Mathematically it can be shown that the effect of decreasing both these parameters simultaneously is to decrease the detention time. Thus the hypothesis tested was not strictly one of differing length configurations but of differing hydraulic residence times. The 200-foot swale has a hydraulic residence time of about 9 minutes, and the 100-foot swale 4.6 minutes.

The 200-foot configuration was monitored for six storm events beginning in the spring of 1991. After all six storms were collected, the swale was converted to the 100-foot configuration. The modifications involved conveying the water via 12-inch PVC pipe from the head of the swale to the swale mid-point and discharging the water through the last 100 feet of the swale.

For both configurations, two monitoring stations were established, one at the swale inlet and the other at the outlet of the swale. Water passed through an H-flume before entering the swale and again at the outlet. Figures 5-2 and 5-3 show the 200-foot and 100-foot swale configurations. The H-flume and sampling station are shown in Figure 5-4. Because of space taken up by the flume, the 200-foot swale had an effective length of only 187 feet and the shorter length was effectively 90 feet.

Flow was measured with a variable resistance depth gauge and recorded using a Unidata data logger. Samples were collected at both inlet and outlet simultaneously, triggered by a signal from the data logger.

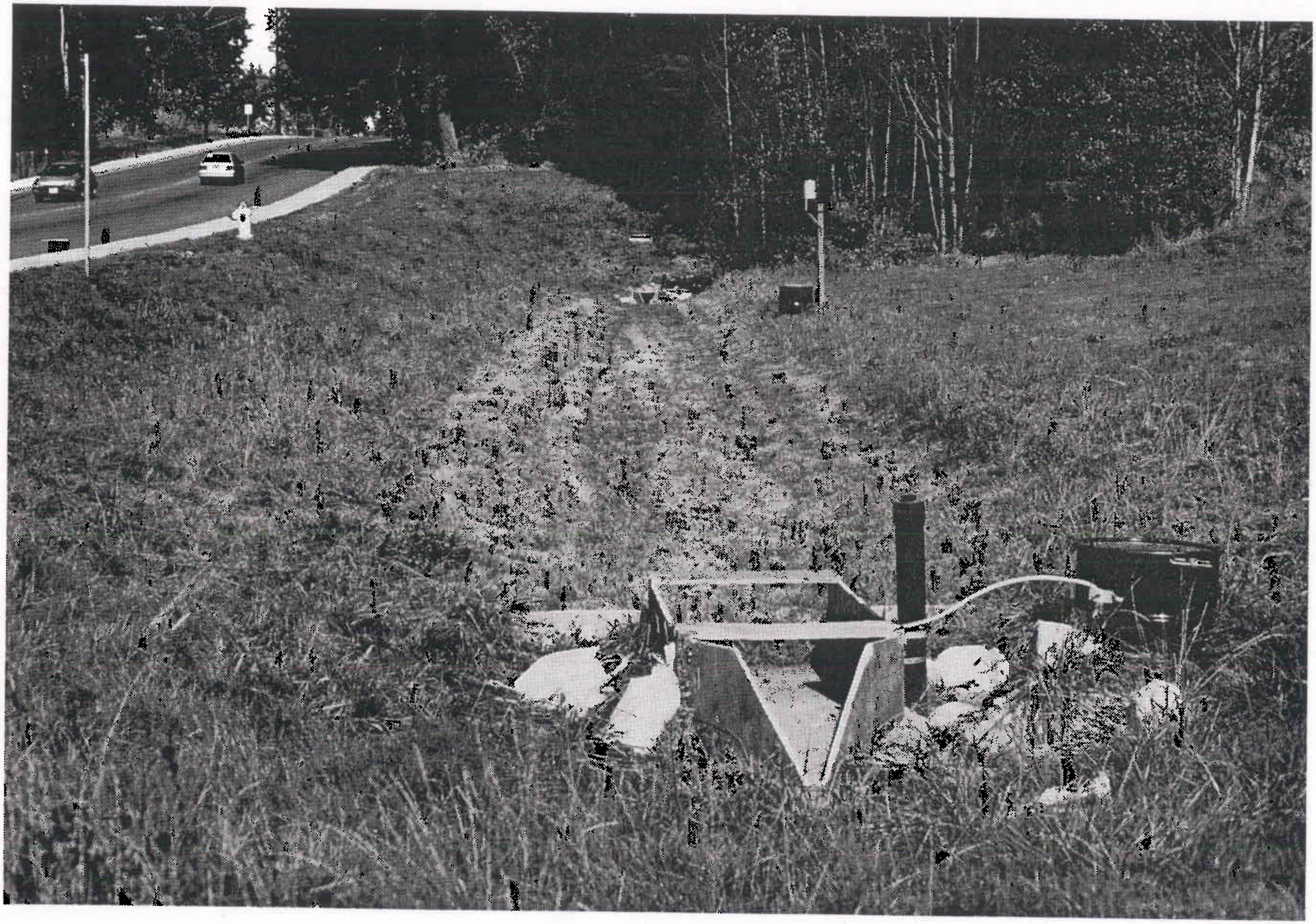

Figure 5-2. 200-foot Swale Configuration

Figure 5-3. 100-foot Swale Configuration

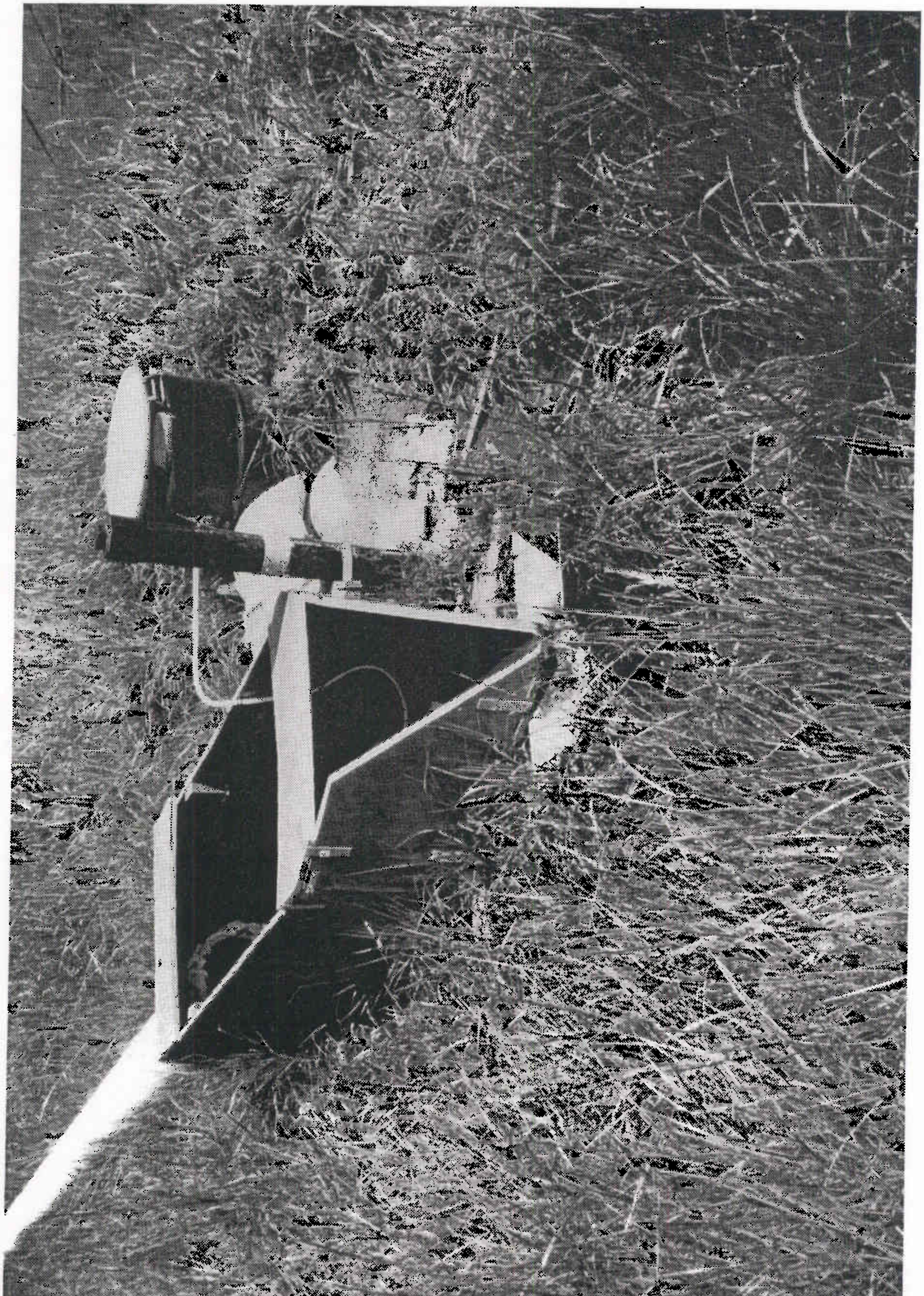

Figure 5-4. H-flume and Sampling Setup

Sampling Methods

In order to characterize adequately the varying pollutant concentrations in samples collected during storm events, current standard practice is to collect flow-weighted composite samples. A flow-weighted composite sample is defined as a single sample that is a composite of many small subsamples that are collected proportionate to the flow volume. It can be done either by taking samples after a specified volume of water has passed, or by adjusting the size of the sample taken at equal intervals. The collection is done over the entire length of the storm event. The pollutant concentrations measured in the composite are event-mean concentrations.

Composite sampling is believed to yield a relatively unbiased measurement of the actual mass loads of pollutants carried during the storm event when the event-mean concentrations are multiplied by the flow volumes. One of the biggest advantages of flow-proportional sampling is that samples from storms with different rainfall characteristics can be compared fairly reliably. Other types of sampling are possible, but are likely to be less representative of the actual total pollutant loads carried. Grab samples represent only one point in time. If taken at the peak of a storm, high flows could increase dilution, and the sample might under represent the actual average pollutant concentrations for the storm. If a fixed volume subsample is taken at uniform time intervals, high flow periods will be under represented and low flow periods over represented. The event-mean concentration might therefore be unreliable.

In this study, flow-weighted composite samples were collected with ISCO brand automatic sampling equipment, triggered by flow information from the data logger, as described above. Subsamples were collected automatically and stored in a central carboy. After the storm, the carboy was retrieved and the flow data were examined to ensure that the samples were collected flow-proportionally over the length of the storm. (The data logger indicates when subsamples were drawn with a "+" on the flow hydrograph. See Appendix D.) The composite sample was then split into separate bottles for laboratory analysis. Part of the sample was filtered before delivery to the laboratory for subsequent metals analysis. Samples were either frozen or taken directly to the laboratory. Sample preservation and holding followed the guidelines given in USEPA (1982). A description of equipment and methods to calculate the flow volumes to be programmed into the equipment are presented in Appendix C.

A field notebook was completed to record information such as equipment installation, equipment programming, date and time of sampling and sample collection, weather and temperature conditions, and any unusual observations.

Storm Event Criteria

Since one goal of the project was to assess the performance of the swale during typical storm events rather than very large storms, rainfall criteria for typical storm sizes were established. Storms were considered representative if they produced between 0.1 and 1.5 inches of rainfall during an 8-hour period.

An additional criterion for an antecedent dry period of at least 48 hours preceding the rainfall event was established to increase the likelihood that detectable pollutant levels would be seen, and to provide rough comparability to requirements for NPDES stormwater sampling. A summary of the rainfall characteristics for the storm events monitored is presented later in this section.

Water Quality Analyses

Previous monitoring studies of biofiltration swale effectiveness have shown removal of total suspended solids and metals varying from poor to excellent (Kercher et al., 1983, Harper et al., 1985, Wang et al., 1981, Oakland, 1983). However, the swales studies were often not specifically designed for pollutant removal. Oakland stated that scouring of the swale at high flows was probably responsible for poor total suspended solids (TSS) removal. An objective of this study was to evaluate a grassy swale designed specifically for pollutant removal. In addition to total suspended solids and metals, other constituents such as nutrients, oil and grease, and fecal coliform bacteria were investigated. The study also examined dissolved and total metals. The variables selected for analysis and analytical method numbers are listed below. Unless stated otherwise, methods are according to Standard Methods for Examination of Water and Wastewater (American Public Health Association, 1985).

Variable		Method Number
Total suspended solids (TSS)		209C
Turbidity		214A
Oil & Grease		503A
Total petroleum hydrocarbons (TPH)		418.1 (USEPA, 1983)
Hardness (three times only)		314B
Metals (total and dissolved*)		
	•Copper (Cu)	305
	•Lead (Pb)	316A
	•Zinc (Zn)	305
	•Aluminum (Al)	305
	•Iron (Fe)	305
Nutrients	•Ortho phosphorus (ortho-P)	424F
	•Total phosphorus (TP)	424C, 424F
	•Bio-available phosphorus (BAP)	Cowen & Lee (1976)
	•Nitrate+nitrite-nitrogen (NO_2+NO_3-N)	418F
Fecal coliform bacteria (FC)		909C

* Dissolved metals are defined as that fraction passing through a 0.45 micron filter.

Except for oil and grease and total petroleum hydrocarbons (TPH), which were grab samples, all samples were flow-proportional samples. Oil and grease and TPH samples were taken manually as grab samples because of requirements of the laboratory analysis method. Samples for oil and grease and TPH were only collected if a sheen was visible.

DATA ANALYSIS

In this section, information about site hydrologic characteristics, storm characteristics, and water quality data will be presented. Pollutant removal efficiency for both the 200- and 100-foot swale configurations are also given.

Hydrology

The amount of stormwater runoff entering the swale from the watershed depends on several factors, including rainfall characteristics, infiltration, ground water discharge (base flow) and, to some extent, the flow delivery setup. Rainfall is the main factor affecting flows in the swale. A rain gauge was installed on site to record rainfall during the sampling period.

The rainfall data for the various storms are analyzed and presented in Table 5-1. Infiltration losses were assumed to be negligible for the swale, since it was underlain with an impermeable layer of glacial till. Evapotranspiration losses were assumed to be negligible because of the short water residence time in the swale. There is, however, base flow from groundwater during the winter months. This base flow varied, but averaged about 0.2 cfs.

Storm Characteristics

Storm samples for the 200-foot configuration were collected between June and October 1991. November 1991 to May 1992 storms were collected for the 100-foot configuration. Because of this sampling schedule, it is expected that data could reflect seasonal variation in storm characteristics.

Rainfall for the summer and early fall storms for the 200-foot configuration ranged from 0.17 to 0.78 inches, and lasted from 2.5 to 7.5 hours in duration. The winter and spring storms sampled for the 100-foot configuration had rainfall amounts of between 0.18 inches and 1.25 inches, the latter being a composite of several small storms over an 11.5-hour period. The shortest storm duration for this period was 3 hours. Complete hydrographs for all storms monitored are given in Appendix D.